Landslide movements and their characteristics, Town of Peace River, Alberta

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ABSTRACT
The Town of Peace River is over a hundred years old. It was heavily urbanized by the late 1970s. Development extended to the geologically immature valley slopes of the Peace River and its tributaries. Triggered by precipitation, developments on these marginally stable slopes have resulted in landslides which caused damage to houses and infrastructure. Landslides directly affect the long-term planning and sustainable development of the community. In this study recent landslides in the Town of Peace River are documented together with their geological conditions and geomorphological features. Displacement records of landslides and possible casual factors are described to show their relationship. Movement patterns obtained from landslide displacements are discussed to explain the modes of the landslides. Observations of movement patterns from recent landslides showed different movement behaviours which indicate the evolution of landslide activity. Movement characteristics observed in this study may be used to estimate the future behaviour of unstable slopes and develop a landslide hazard map for the Peace River area.

RÉSUMÉ
La ville de Peace River a plus de cent ans. A la fin des années 1970 elle été fortement urbanisée. Les bâtiments s'étendaient aux pentes géologiquement immature de la vallée de la Rivière de la Paix et de ses affluents. Déclenchée par la précipitation, cette construction sur des pentes très peu stables a entraîné les glissements de terrain qui a causé des dommages à l'infrastructure et aux maisons. Les glissements de terrain affectent directement la planification à long terme et le développement durable de la communauté. Cette étude documente les glissements de terrain récents dans la ville de Peace River ainsi que leurs conditions géologiques et géomorphologiques. Les enregistrements des déplacements des glissements de terrain et des facteurs occasionnels possibles sont décrits pour montrer le rapport entre les deux. Les modèles des mouvements obtenus à partir de déplacements de glissements de terrain sont étudiés pour expliquer les modes des glissements de terrain. Les observations de modèles des mouvements des glissements de terrain récents ont montré les comportements différents des mouvements qui indiquent l'évolution de l'activité de glissements de terrain. Les caractéristiques observées dans cette étude peuvent servir à estimer le comportement futur des pentes instables et élaborer un plan de risque de glissements de terrain pour la région de la Rivière de la Paix.

1 INTRODUCTION

With emerging threats of geological hazards in urban areas, interdisciplinary research was initiated at the Town of Peace River in 2006 to characterize the types and extents of landslides in and around the municipality (Froese 2007). Results of studies will provide a better understanding of geohazards and support future development plans in the study area. This paper describes some work done to catalogue recent landslides and the general characteristics of their movement behaviours. This information, in turn, provides an insight into the framework of a future landslide hazard assessment system in the Town of Peace River.

2 DESCRIPTION OF THE STUDY AREA

The Town of Peace River and its adjacent gently rolling lowland areas (the Peace River Lowland) have been developed as an agricultural resource and transport service point covering a very large area (Peace River Regional Planning Commission 1971). As the town grew in 1970, terraces were fully packed and development commenced on valley slopes. Unfortunately many valleys in the Peace River Lowland are relatively young from a geological point of view and consequently unstable. Valley slopes may move after even a small disturbance.

The general surface topography forms semi-continuous uplands, broad prairies with gentle slopes and deeply incised river valleys with steep slopes (Sharma 1970). The west side of the river has longer and gentler slopes up to flat forested uplands; steep slopes in the east bank lead to uplands with the steep ravines of tributaries of the Peace River (Heart River and Pat's Creek). Uplands and prairies have been used as crop land but steep slopes retain their natural shapes except where cut by major transportation routes (Figure 1).

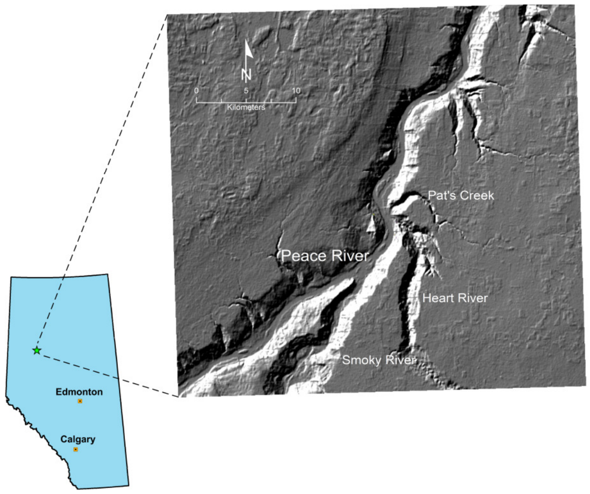

Figure 1. Peace River District focusing on the Town of Peace River. Shaded relief image is obtained from SRTM dataset.

The climate characteristic of the Peace River Lowland can be categorized based on the Köppen-Geiger Climate Classification as snow (main climates), fully humid (precipitation) with cool summer (Kottek et al. 2006). Located in the northwest of the forest and parkland region of Alberta, this area has the typical weather of the Western Prairies, a moderately warm summer and a relatively cold winter (Jones 1966). Precipitation increases westward and the majority is rainfall in summer. The water equivalent of total snowfall is the larger part of precipitation in winter. Snow-covered drainage basins melt in spring and cause high infiltration. With heavy rainfalls in spring, they raise ground water levels.

The Peace River Lowland consists of several geological features which are results of repetitive erosion and deposition. While preliminary geological studies of the Peace River Lowland began in the late 1800s, Rutherford (1930) first described comprehensively the geology and water resources in the Peace River and Grande Prairie areas. Studies for government as well as industry of the Peace River Lowland by Borneuf (1981), Jones (1966), Taylor (1960) and Tokarsky (1971) were at regional scale and provided limited details of the surficial deposits. Leslie and Fenton (2001) reported complete glacial stratigraphy as well as bedrock formations and surficial sediments of the Peace River area. Recent work by Morgan et al. (2008) updated bedrock topography and Quaternary stratigraphy in the Peace River Lowland from multiple data sources.

3 RECENT LANDSLIDES IN THE TOWN OF PEACE RIVER

Landslides in the Peace River Lowland have been well documented by Cruden et al. (1993; 1997), Cruden and Miller (2001), Kim et al. (2010), Lu et al. (1998) and Miller and Cruden (2002). Although these studies are useful for understanding the mechanisms of the landslides which occurred in the Peace River Lowland, they are relatively remote from the incorporated area. Detailed local studies on the landslides in the Town of Peace River focused on the instabilities of slopes in residential areas and infrastructure like highways and railways. An early study by Hardy (1957) reported engineering experience of landslides in clay shale along the old highway in Pat's Creek. Sharma (1970) described strength properties of the postglacial lake sediments exposed along a portion of Highway No. 2 near the Town of Peace River. Ruel (1988) and Cruden et al. (1990) reported a landslide affecting the Canadian National Railway in the Heart River valley. This landslide was also examined to establish remedial measures for the maintenance of the Secondary Highway 744 (Diyaljee 1992). Barlow et al. (1991) suggested effective mitigation approaches against the landslides in the residential subdivisions on the east bank of the Peace River.

3.1 Recent landslides inventory

In this study, landslides which have occurred in the Town of Peace River since the 1970s, when developments encroached on slopes for residential subdivisions, are collected as an event-based inventory (van Westen et al. 2008). This event-based inventory helps to identify major triggering causal factors which drive landslides and provides an understanding of mechanisms for the

Table 1. Landslides in the Town of Peace River since 1970.

No[1]	Location	Date[2]	Type	Adjacent infrastructure
1	Mile 47.8	1993	Translational slide / Rotational slide	Railway
2	Mile 47.6	1984	Translational slide	Railway / Road
3	Mile 46.5	1978	Translational slide	Railway
	99/101st. - End of 101st.	1992	Translational slide	Residential area
4	99/101st. - Transition zone	1973	Translational slide	Residential area
	99/101st. - End of 99st.	1985	Translational slide	Residential area
5	Shop slide	1985	Translational slide	Road
6	Mile 50.9	1979	Flow	Railway

[1] Numbers are shown in Figure 2
[2] Represents the year of initial movements (displacement, cracks etc.)

reactivation of old landslides. Six landslides on the slopes in the Town of Peace River are collected from the various technical reports published by either local municipalities or industries. Four landslides are located in the east bank which has relatively steep slopes, the others are on gentle slopes of the west bank of the river valley. All of them are located in residential areas or close to roads and railways. Spatial distribution of these selected landslides is described in Figure 2 and general information is summarized in Table 1.

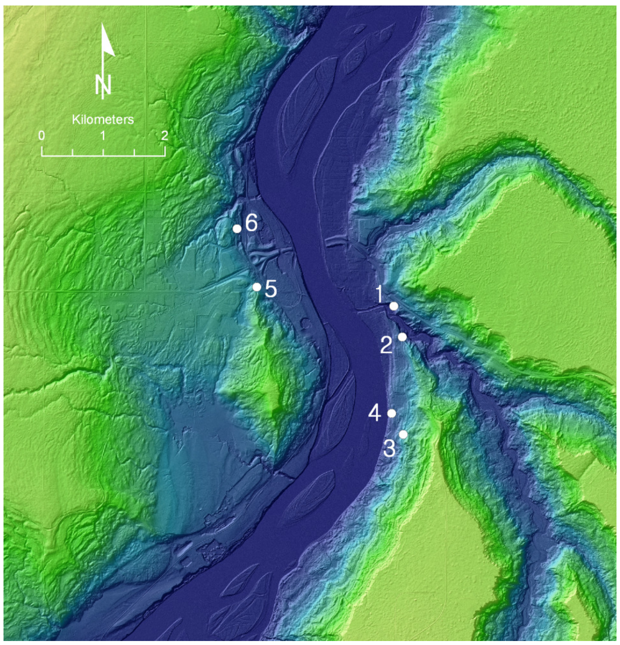

Figure 2. Distribution of recent landslides in the Town of Peace River. Peace River flows northward and numbers represent the location of each landslide: 1 - Mile 47.8; 2 - Mile 47.6; 3 - Mile 46.5; 4 - 99/101st.; 5 - Shop slide; 6 - Mile 50.9.

3.2 Data analysis

Boreholes installed in the six landslides are used to identify their movement characteristics during the development of each landslide. This information also helps to identify appropriate causal factors to generate landslide inventory for the hazard and risk assessments. A total of 23 boreholes in which slope inclinometers were installed since the initiation of movements were compiled for this study and 48 points within them moved. From these borehole data, analysis was performed to calculate movement rates as well as elevations, moisture contents and subsurface profile in the rupture surfaces.

Figure 3 shows the total movement rates obtained from the 48 points indicating as movements in 23 boreholes. Results of analyzing movement rates show that most movement rates are in the very slow (1600 mm/year to 16 mm/year) and extremely slow (less than 16 mm/year) classes (IUGS Working Group on Landslides 1995). Under these conditions, structures may be undamaged or have manageable damages If cracks occurred by movements.

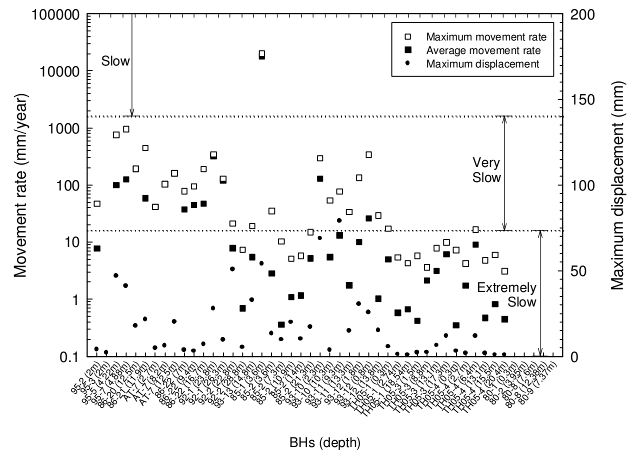

Figure 3. Total movement rates obtained from the slope inclinometer data. Maximum and average values of movement rates are described. Maximum displacement of each borehole is also shown.

Cumulative displacements obtained from the slope inclinometers were also plotted against time to show the impact of external causal factors such as rainfall and seasonal fluctuations. Landslide movements in 1 and 4 (Table 1) are shown in Figure 4. Major movements are, at the most, slow, and correlated with the cumulative precipitation during the measuring periods.

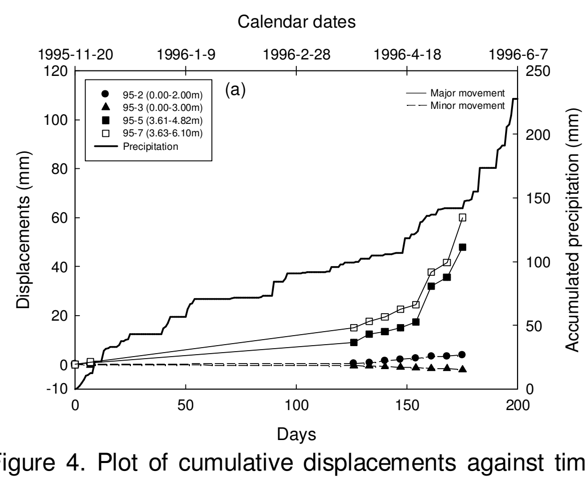

Figure 4. Plot of cumulative displacements against time. a. Mile 47.8 landslide. Cross-sections of each landslide in Figure 5 show the location of boreholes. Locations of slides are indicated in Figure 2.

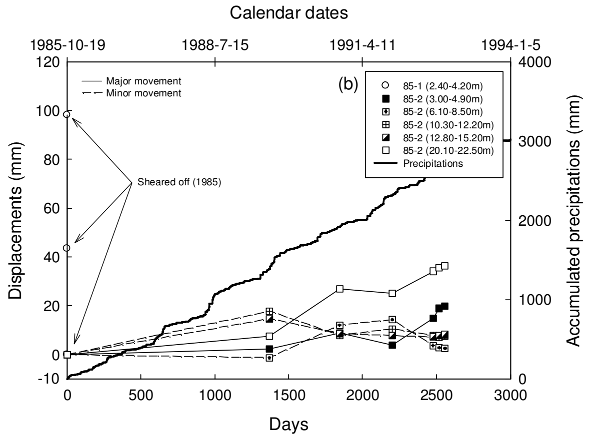

Figure 4 (Cont'd). b. 99/101st. - End of 99st. landslide.

4 MOVEMENT CHARACTERISTICS AND THEIR BEHAVIOURS

Monitoring of landslide movements causing instability has become common practice in most slope related projects. Movements could indicate relationships with factors affecting their behaviours. Due to the development of instrumentation, we can capture reliable data which explain actual landslide mechanisms. Therefore, movement characteristics expressing displacement, velocities and accelerations in landslides could give insights during and even prior to hazardous situations.

4.1 Material failure relationship

Rate-dependent material failure was proposed by Saito and Uezawa (1961) and Saito (1969; 1970) indicating a close relationship between creep induced rupture life and strain rate. Voight (1988) generalized the behaviour of materials in terminal stages under conditions of approximately constant stress and temperature. This behaviour has been used to predict the time of landslide occurrence (Fukuzono 1990). Several variations (exponential and power laws) were proposed and evaluated by practical examples (Cornelius and Scott 1993; Cruden and Masoumzadeh 1987).

Recent development by Petley (2004) and Petley and others (2002; 2005) indicates typical material failure modes based on different movement behaviours. From a large number of landslide movement records, they postulated that a linear plot of the reciprocal of velocity against time represented a brittle failure mechanism where a landslide occurs on a discrete rupture surface. Ductile movements within a shear zone form an asymptotic or non-linear tendency. In other words, rupture surfaces newly-generated by crack propagation show linear behaviours whereas non-linear trends are usually found on existing rupture surfaces or bedding planes (Figure 6). Different movement behaviours, therefore, become indicators of both current and future activity of landslides.

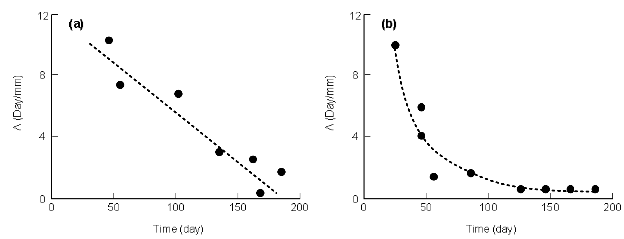

Figure 6. Typical material failure modes found in landslides. a. Linear trend. b. Non-linear or asymptotic trend.

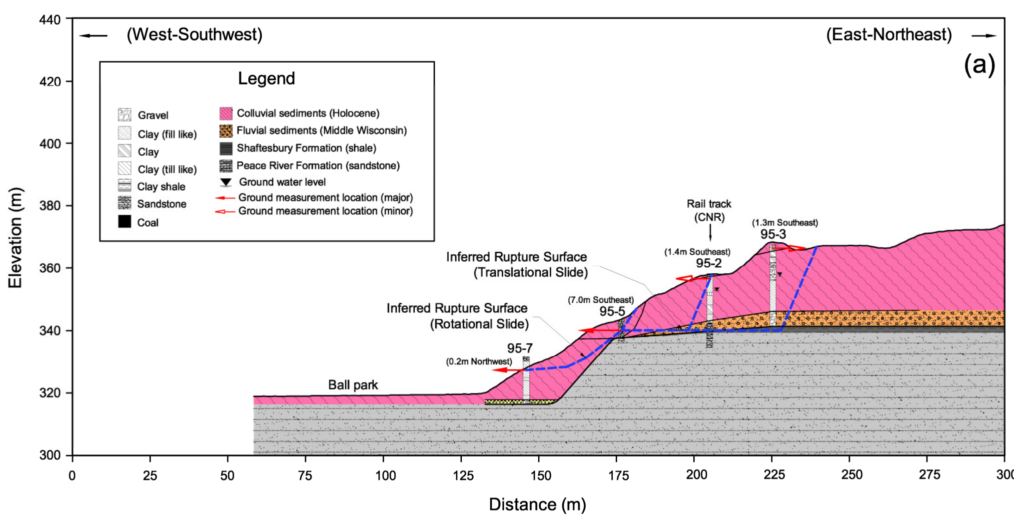

Figure 5. Cross-section of the landslide area. a. Mile 47.8 landslide.

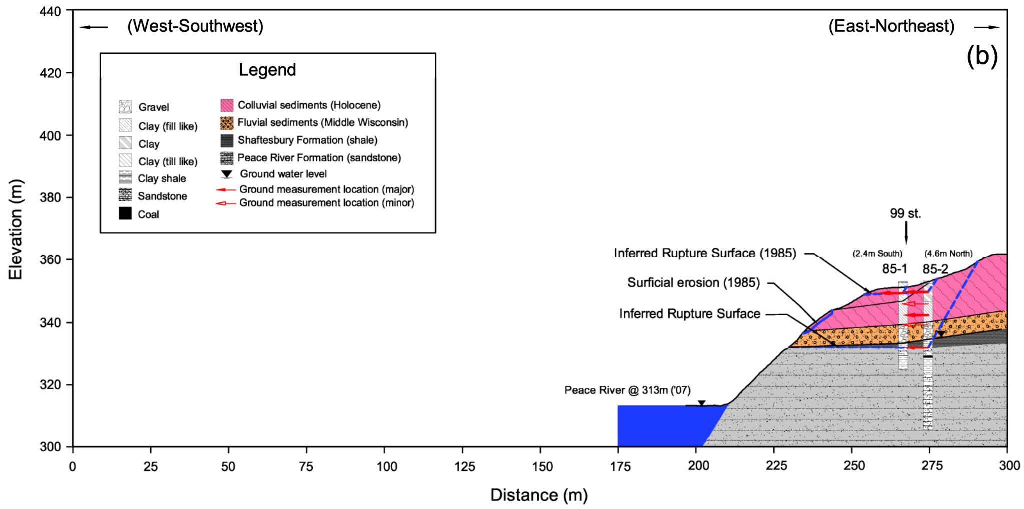

Figure 5 (Cont'd). b. 99/101st. - End of 99st. landslide.

4.2 Analyzing movement behaviours

Figure 7 shows several movement records obtained from Mile 47.8 landslide described in Figure 2 and Table 1. Landslide movements were taken from the slope inclinometers installed in the slide. Locations of each borehole holding slope inclinometers are indicated in the cross-section (Figure 5).

Figure 7a shows movement behaviours obtained from the boreholes 95-5 and 7. From the linear behaviour, we can postulate that landslide movement within this part of the slope occurred on a newly-generated rupture surface. Specifically, movements had started from several fractures and when these fractures exceeded a threshold indicated in Figure 7a, fractures combined to form a rupture surface which then propagated. The linear behaviours above the threshold could be explained by crack propagation along the rupture surface.

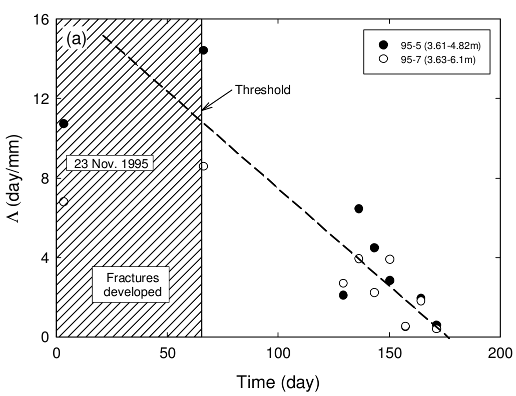

Figure 7. Landslide movement patterns obtained in Mile 47.8 landslide. a. Movement behaviours obtained from the boreholes 95-5 and 7. Location of slide is indicated in Figure 2.

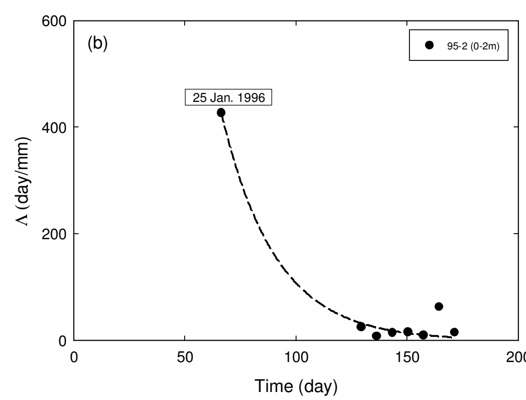

Figure 7 (Cont'd). b. Movement behaviour obtained from the borehole 95-2.

On the other hand, movement of borehole 95-2 (Figure 7b) showed an asymptotic trend. Unlike the behaviour on the existing rupture surfaces or bedding planes described above, this non-linear trend seemed to be affected by landslide movements in front of borehole 95-2. After significant movement, the adjacent slope had undergone either a decrease in driving force (perhaps by drainage) or an increase in resisting force (perhaps by friction with velocity) which resulted in this non-linear behaviour.

Another example is shown in Figure 8, which presents movement behaviours obtained from 99/101st. landslide. Movement obtained from the top of borehole 85-1 (Figure 8a) shows a linearity possibly caused by rupture surface propagation. It can also forecast the approximate time to rupture by extending the linear trend to meet the abscissa of the plot (Fukuzono 1990). Because the uncertainty and lack of data for estimation are apparent, the estimate of time to rupture seems to be inconsistent with the time of actual rupture.

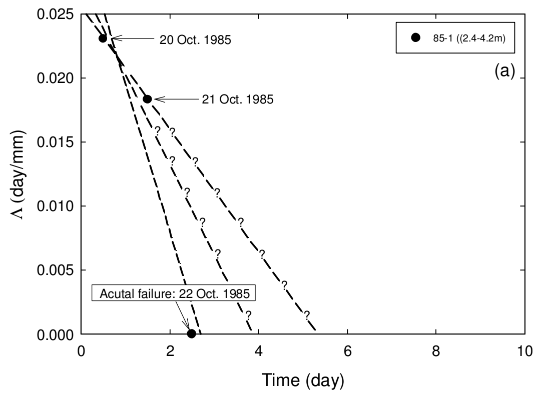

Figure 8. Landslide movement patterns obtained in End of 99st. landslide, which is part of the 99/101st. landslide. a. Movement behaviours obtained from the borehole 85-1. Location of slide is indicated in Figure 2.

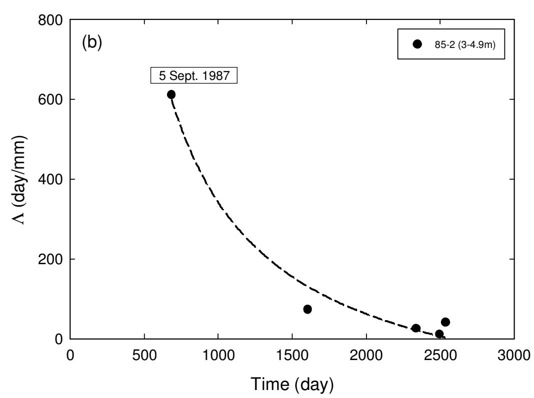

Figure 8 (Cont'd). b. Movement behaviour obtained from the top of borehole 85-2.

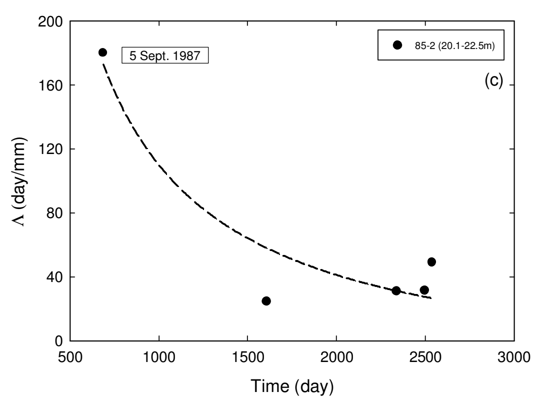

Figure 8 (Cont'd). c. Movement behaviour obtained from the bottom of borehole 85-2.

Figure 8b shows movement behaviour of the top of borehole 85-2 showing a non-linear trend similar to the movement present in Figure 7b. The movement pattern obtained at the lowest point in borehole 85-2 (Figure 8c), however, represents movement on existing rupture surfaces or bedding planes. It can be reasonably postulated that the elevation of this movement is consistent with the Shaftesbury Formation, which has undergone of glacial disturbance and become sheared in the past. Movements occurred at intermediate elevations in the borehole 85-2 (Figure 8d) produced an internal deformation due to seasonal fluctuations.

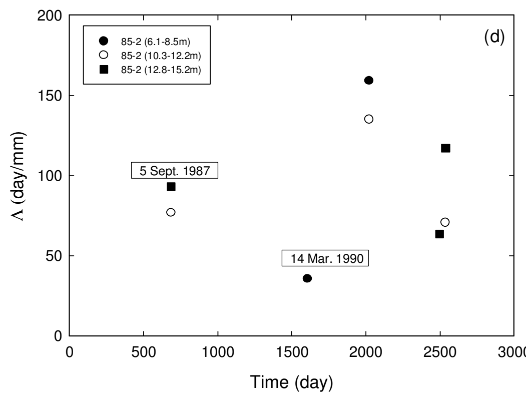

Figure 8 (Cont'd). d. Movement behaviours in the middle of borehole 85-2.

4.3 Discussion and future application

Empirical approaches based on monitoring surface or subsurface movements of landslides explicitly and directly estimate the time intervals to peak landslide velocities if provided with sufficient, reliable movement observations. However, these approaches do not consider the kinematics of rupture or the properties of the materials which are being deformed.

The uncertainties in determining movement patterns, whether linear or non-linear, make estimation of the time to peak velocity difficult. As Heim (1932) showed, internal deformation due to seasonal fluctuations can be misunderstood as an accelerating movement leading to a forecast of a catastrophic landslide. One well-known pitfall of this method is that few reports of the successful prediction of time of rupture of a landslide exist (Hungr et al. 2005). Therefore, it seems to take more study of mechanisms, rupture surface development and deformation within slopes to achieve reliable results predicting the ruptures of landslides.

Practically, however, these can provide insights into formation and propagation of rupture surfaces. Figure 9 shows an internal deformation in the Shop slide, one of landslides in the Town of Peace River. Movements from boreholes TH05-3 and 4 started in different forms, then present consistent behaviours about 600 days later which means that they are in the same displacing mass and move along the general rupture surface within the slope.

Another application is as a warning threshold. Because of the lack of precise estimates of the times of rupture, this can be used only as a warning alert (Salt 1988). Together with the consideration of external conditions (such as precipitation or earthquake) and zonation of potential areas by landslide hazard assessment it would be a powerful tool for managing landslides in the future.

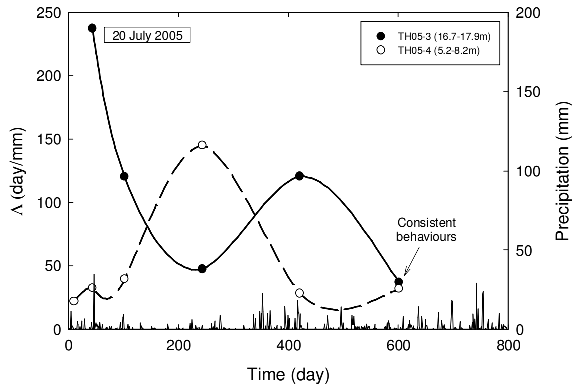

Figure 9. Landslide movement patterns obtained in the Shop slide. Location of slide is indicated in Figure 2.

5 CONCULSIONS

Research initiated in 2006 into emerging geological hazards in urban areas of the Town of Peace River provides a better understanding of geohazards and supports future development plans. In this study, six landslides which have occurred in the Town of Peace River since the 1970s are collected and their displacement records are described to show relationships with possible casual factors. Observations of movement patterns from recent landslides show different movement behaviours (linear or non-linear) indicating the progress of landslide activities. Movement characteristics observed in this study might be used to estimate the future behaviour of unstable slopes and develop landslide hazard assessments for the Peace River area such as warning thresholds and guidelines for the areas' zonation.

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